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Combination of CMS searches for heavy resonances decaying to pairs of bosons or leptons

CMS Collaboration ; Canelli, M Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Brzhechko, Danyyl ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Leontsinis, Stefanos ; Mikuni, Vinicius Massami ; Neutelings, Izaak ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Wertz, Sebastien ; Zucchetta, Alberto ; et al

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DOI: <https://doi.org/10.1016/j.physletb.2019.134952>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-180104>

Journal Article

Published Version



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Originally published at:

CMS Collaboration; Canelli, M Florencia; Kilminster, Benjamin; Aarrestad, Thea K; Brzhechko, Danyyl; Caminada, Lea; de Cosa, Annapaoloa; Del Burgo, Riccardo; Donato, Silvio; Galloni, Camilla; Leontsinis, Stefanos; Mikuni, Vinicius Massami; Neutelings, Izaak; Rauco, Giorgia; Robmann, Peter; Salerno, Daniel; Schweiger, Korbinian; Seitz, Claudia; Takahashi, Yuta; Wertz, Sebastien; Zucchetta, Alberto; et al (2019). Combination of CMS searches for heavy resonances decaying to pairs of bosons or leptons. Physics Letters B, B798:134952.

DOI: <https://doi.org/10.1016/j.physletb.2019.134952>



Combination of CMS searches for heavy resonances decaying to pairs of bosons or leptons

The CMS Collaboration^{*}

CERN, Switzerland

ARTICLE INFO

Article history:

Received 31 May 2019

Received in revised form 14 August 2019

Accepted 16 September 2019

Available online 23 September 2019

Editor: M. Doser

Keywords:

CMS

B2G

Diboson

Dilepton

HVT

Graviton

ABSTRACT

A statistical combination of searches for heavy resonances decaying to pairs of bosons or leptons is presented. The data correspond to an integrated luminosity of 35.9 fb^{-1} collected during 2016 by the CMS experiment at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV. The data are found to be consistent with expectations from the standard model background. Exclusion limits are set in the context of models of spin-1 heavy vector triplets and of spin-2 bulk gravitons. For mass-degenerate W' and Z' resonances that predominantly couple to the standard model gauge bosons, the mass exclusion at 95% confidence level of heavy vector bosons is extended to 4.5 TeV as compared to 3.8 TeV determined from the best individual channel. This excluded mass increases to 5.0 TeV if the resonances couple predominantly to fermions.

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1. Introduction

Over the past half century, successive searches for heavy resonances in two-body decays have often led to discoveries of new states. At the CERN LHC, searches for W' and Z' resonances (collectively referred to as V') that couple through the electroweak (EW) interaction to standard model (SM) particles have been performed by ATLAS and CMS in final states with two SM bosons [1–18], two leptons [19–22], and two light-flavor [23,24] or heavy-flavor quarks [25–29]. These new states would couple predominantly to either SM fermions, as in the case of minimal W' and Z' models [30–32], or SM bosons, as in strongly coupled composite Higgs and little Higgs models [33–39]. In addition, models based on warped extra dimensions provide a candidate for a massive resonance, such as the spin-2 first Kaluza-Klein excitation of the graviton (G) [40–42]. In bulk graviton models [43], the SM fermions and gauge bosons are located in the bulk five-dimensional spacetime, and the graviton has a sizable branching fraction to pairs of W , Z , and H bosons.

This Letter describes a statistical combination of CMS searches for heavy resonances that decay to pairs of bosons or leptons [1–10,19,20]. The event selection, the simulated samples, the background estimation, and the systematic uncertainties of the individual analyses are unchanged. The results are used to set exclusion

limits on models that invoke heavy vector resonances and on a model with a bulk graviton.

The SM bosons produced in the decay of resonances X with masses m_X that exceed 1 TeV are expected to have a large Lorentz boost [44]. The decay products of the SM bosons are therefore highly collimated, requiring dedicated techniques for their identification and reconstruction. In the case of hadronic decays, the pair of quarks produce a single large-cone jet with a two-prong structure. In addition, Higgs bosons can also be identified by tagging the b quarks originating from their decays. In models where heavy vector bosons couple predominantly to fermions, the combined contribution from the leptonic decays $W' \rightarrow \ell\nu$ and $Z' \rightarrow \ell\ell$ dominates, and these channels [19,20] are included in the combination, providing complementary sensitivity to the searches in diboson channels. The analyses considered in this Letter are based on a data sample of proton-proton (pp) collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment in 2016, and corresponding to an integrated luminosity of 35.9 fb^{-1} . A similar combination performed on a comparable set of data has been recently published by ATLAS [45].

2. The CMS detector and event reconstruction

The CMS detector features a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. These detectors reside within a

^{*} E-mail address: cms-publication-committee-chair@cern.ch.

superconducting solenoid, which provides a magnetic field of 3.8 T. Forward calorimeters extend the pseudorapidity coverage up to $|\eta| < 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector, together with a definition of the coordinate system and the kinematic variables, can be found in Ref. [46].

The information from various elements of the CMS detector is used by a particle-flow (PF) algorithm [47] to identify stable particles reconstructed in the detector as electrons, muons, photons, and charged or neutral hadrons. The energy of electrons is determined from a combination of the electron momentum, as determined in the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The dielectron mass resolution for $Z \rightarrow ee$ decays ranges from 1.9% when both electrons are in the ECAL barrel, to 2.9% when both electrons are in the endcaps [48]. The momentum of muons is obtained from the curvature of the corresponding track. The p_T resolution in the barrel is better than 7% for muons with p_T up to 1 TeV [49]. The τ leptons that decay to hadrons and a neutrino (labeled τ_h) are reconstructed by combining one or three charged PF candidates with up to two neutral pion candidates [50]. The e , μ , and τ_h with large momenta are required to be isolated from other hadronic activity in the event. The energy of charged hadrons is determined from a combination of their momenta measured in the tracker and the matching ECAL and HCAL energy deposits. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Jets are reconstructed from PF candidates clustered with the anti- k_T algorithm [51], with a distance parameter 0.4 (AK4 jets) or 0.8 (AK8 jets), using the FASTJET 3.0 package [52,53]. The geometrical overlaps between jets and isolated leptons, and between AK4 jets and the AK8 jet, are handled by assigning the overlapping four-momentum to the lepton, and the AK8 jet, respectively. The four-momenta of the AK4 and AK8 jets are obtained by clustering candidates passing the charged-hadron subtraction algorithm [54]. The contribution of neutral particles originating from additional pp interactions within the same or neighboring bunch crossings (pileup) is proportional to the jet area, and is estimated using the median area method implemented in FASTJET, and then subtracted from the jet energy. The jet energy resolution, after the application of corrections to the jet energy, is 4% at 1 TeV [55]. The missing transverse momentum vector \vec{p}_T^{miss} is computed as the negative vector sum of the transverse momenta of all the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [56]. The \vec{p}_T^{miss} is corrected for adjustments to the energy scale of the reconstructed AK4 jets in the event.

While AK4 jets are used for single quarks, AK8 jets are adopted to reconstruct large momentum SM bosons that decay to quarks. Reconstructing the AK8 jet mass (m_j) and substructure relies on the pileup-per-particle identification algorithm [54,57]. The contributions from soft radiation and additional interactions are removed using the soft-drop algorithm [58,59], with parameters $\beta = 0$ and $z_{\text{cut}} = 0.1$. Dedicated mass corrections, obtained from simulation and data in a region enriched with $t\bar{t}$ events with merged $W(q\bar{q})$ decays, are applied to the jet mass to reduce any residual jet p_T dependence [6,60], and to match the jet mass scale and resolution observed in data. The measured soft-drop jet mass resolution is approximately constant at 10% in the considered range of jet p_T [60]. Exclusive m_j intervals labeled m_W , m_Z , and m_H , which range from 65 to 85, 85 to 105, and 105 to 135 GeV, respectively, are defined according to the SM boson masses and the jet mass resolution.

Hadronic decays of W and Z bosons are identified using the ratio between 2-subjettiness and 1-subjettiness [61], $\tau_{21} = \tau_2/\tau_1$.

The variables m_j and τ_{21} are calibrated using a top quark-antiquark sample enriched in hadronically decaying W bosons [62]. The decay of a Higgs boson to a pair of b quarks is identified using one of two b tagging algorithms, depending on the background composition. The first consists of a dedicated b tagging discriminator, specifically designed to identify a pair of b quarks clustered in a single jet [63]. The second relies on splitting the AK8 jet into two subjets, then applying the combined secondary vertex algorithm [63] to the subjets. The latter is also applied to AK4 jets to identify isolated b quarks in the event.

3. Signal modeling

The response of the CMS detector to the production and decay of heavy resonances is evaluated through simulated events, which are reconstructed using the same algorithms as used in collision data. The spin-1 gauge bosons, W' and Z' , are simulated at leading order (LO) using the MADGRAPH5_aMC@NLO 2.4.2 matrix element generator [64], in the heavy vector triplet (HVT) framework [65,66], which introduces a triplet of heavy vector bosons with similar mass, of which one is neutral (Z') and two are electrically charged (W'^{\pm}). The coupling strength of the heavy vector bosons to SM bosons and fermions is determined from the combinations $g_H = g_V c_H$ and $g_f = g^2 c_F / g_V$, respectively. The parameter g_V is the strength of the new interaction; c_H characterizes the interaction between the HVT bosons, the Higgs boson, and longitudinally polarized SM vector bosons; c_F represents the direct interaction between the V' bosons and the SM fermions; g is the SM $SU(2)_L$ gauge coupling constant. The HVT framework is presented in two scenarios, henceforth referred to as model A and model B, depending on the couplings to the SM particles [66]. In the former, the coupling strengths to the SM bosons and fermions are comparable, and the new particles decay primarily to fermions. In the latter, the couplings to the SM fermions are small, and the branching fraction to the SM bosons is nearly 100%. Events are simulated with different m_X hypotheses from 800 to 4500 GeV for X decays to bosons, and 800 to 5500 GeV for X decays to leptons, assuming a negligible resonance width compared to the experimental resolution (3–20%). The kinematic distributions of the signal do not depend on the choice of benchmark scenario, and the samples are reweighted according only to the cross sections and branching fractions.

The bulk graviton events are also simulated at LO using the same MADGRAPH5_aMC@NLO generator. The cross section and the width of the bulk graviton mainly depend on its mass and the ratio $\tilde{\kappa} \equiv \kappa / \bar{M}_{\text{Pl}}$, where κ is a curvature factor of the model and \bar{M}_{Pl} is the reduced Planck mass [43,67]. The graviton signals are generated assuming $\tilde{\kappa} = 0.5$, which guarantees that the width of the graviton is smaller than the experimental resolution.

The signal events are generated using the NNPDF 3.0 [68] parton distribution functions (PDFs), and are interfaced to PYTHIA 8.205 [69] for parton showering and hadronization, adopting the MLM matching scheme [70]. Simulated pileup interactions are superimposed on the hard process, and their frequency distribution is weighted to match the number of interactions per bunch crossing observed in data. Generated events are processed through the CMS detector simulation, based on GEANT4 [71].

4. Search channels

The search strategies for the analyses contributing to the combination are summarized in this Section. More details are provided in the relevant publications [1–10,19,20].

4.1. Fully hadronic diboson channels

Diboson resonances have been searched for in several final states, depending on the decay modes of the bosons. The final states targeted were $VV \rightarrow q\bar{q}q\bar{q}$ [1], $VH \rightarrow q\bar{q}b\bar{b}$ [6], and $HH \rightarrow b\bar{b}b\bar{b}$ final states [9,10]. Each boson is reconstructed as a two-prong, large-cone jet, so that for diboson resonances, the two jets would recoil against each other. The presence of a diboson resonance would be observed in the dijet invariant mass spectrum m_{jj} . The W and Z bosons are identified (V tagged) via the m_j and τ_{21} variables, and b tagging is used to identify b quarks from Higgs bosons in addition to m_j . Although the signal yield is large, because of the large fraction of Higgs boson decays to b quarks, these channels are subject to an overwhelming background from quantum chromodynamics (QCD) multijet production.

In the VV and VH analyses, the background is estimated directly from data, assuming that the invariant mass distribution of the background can be described by a smooth, parameterizable, monotonically decreasing function of m_{jj} . The signal template, based on a Gaussian core, is fitted to the data simultaneously with the background function. The HH analyses also use an additional region in the fit, obtained by inverting the b tagging selection on the H candidates, which constrains the parameters of the background function.

4.2. Semi-leptonic diboson channels

Searches for VV, VH, and HH resonances have been performed in channels where one of the SM bosons decays to leptons and the other to quarks ($ZV \rightarrow \nu\nu q\bar{q}$ [2], $WV \rightarrow \ell\nu q\bar{q}$ [3], $ZV \rightarrow \ell\ell q\bar{q}$ [4], $ZH \rightarrow \nu\nu b\bar{b}$ [7], $WH \rightarrow \ell\nu b\bar{b}$ [7], $ZH \rightarrow \ell\ell b\bar{b}$ [7], $VH \rightarrow q\bar{q}\tau\tau$ [8] and $HH \rightarrow b\bar{b}\tau\tau$ [8]). These final states represent an attractive alternative to all-jet final states, thanks to the large selection efficiencies and natural discrimination against multijet background stemming from the presence in the signal of energetic and isolated leptons or neutrinos.

The decay of a Z boson to neutrinos can be identified through its large p_T^{miss} , and the resonance mass can be inferred from the transverse mass between the \vec{p}_T^{miss} and the jet originating from the hadronic decay of the other boson. For the $W \rightarrow \ell\nu$ decay, there is a single, isolated lepton associated with a moderate p_T^{miss} , and the vector boson can therefore be reconstructed by imposing a constraint from the W boson mass to recover the longitudinal momentum of the neutrino. In $Z \rightarrow \ell\ell$ decays, two opposite-sign, same-flavor leptons with a combined invariant mass compatible with the Z boson mass are used to determine accurately the Z boson four-momentum. A Higgs boson decaying to τ leptons is identified from dedicated τ_h decay reconstruction and isolation techniques [8], and its mass is estimated through the measured momenta of the visible decay products of the τ leptons and the \vec{p}_T^{miss} , with the SVFIT algorithm [72]. The boson that decays to a pair of quarks is reconstructed as an AK8 jet. The AK8 jet mass is required to be compatible with either the W and Z boson masses, denoted as m_V ($65 < m_j < 105$ GeV), or the Higgs boson mass ($105 < m_j < 135$ GeV).

In the semi-leptonic analyses, the main V + jets background is estimated from a fit to data in the m_j sidebands of the hadronic jet, and extrapolated to the signal region using a transfer function (“ α function”) obtained from simulation. The top quark pair production is estimated from simulation, but its normalization is rescaled to match the data in control regions obtained by requiring an additional b-tagged AK4 jet in the event [2,7,8].

In addition, the $WV \rightarrow \ell\nu q\bar{q}$ analysis introduces a novel signal extraction method based on a two-dimensional (2D) fit to data [3]. The backgrounds are separated into non-resonant and resonant

categories depending on the presence or absence of W bosons and top quarks in the jet mass spectrum, and are fitted simultaneously in the space of m_j and m_{VV} , accounting for the correlation between the two variables.

4.3. Fully leptonic diboson channels

Searches for diboson resonances decaying to a pair of Z bosons have been performed in fully leptonic final states, with one boson undergoing the decay $Z \rightarrow \ell\ell$ and the other $Z \rightarrow \nu\nu$ [5]. The presence of the leptons and neutrinos defines a very clean final state with reduced backgrounds, but the small branching fraction makes this channel competitive only for small resonant mass values.

4.4. Decays to a pair of fermions

The decay of a heavy resonance to a pair of fermions can be sizable when the couplings to SM fermions are large. If the resonance is electrically charged, as in the case of W'^{\pm} , the decay to a neutrino and an electron or muon yields a broad excess in the $\ell\nu$ transverse mass spectrum [19]. If the new state is neutral, as in the case of Z' , a narrow resonance would emerge from the dilepton or dimuon ($\ell\ell$) invariant mass spectra [20]. The analyses of these fermionic decays extend to masses above 5 TeV, and employ selection techniques optimized to identify and measure very energetic electrons and muons in the detector [19,20].

5. Event selection

The search regions of the analyses entering in the combination are statistically independent because of mutually exclusive selections on the number of leptons and their flavor, number of AK8 jets, and jet mass intervals. Analyses with hadronic final states reject events with isolated leptons or with large p_T^{miss} . Overlaps between channels that share the same lepton multiplicity are avoided by selecting different jet mass ranges. The $W' \rightarrow \ell\nu$ search does not share any events with the $W' \rightarrow WV$ and $W' \rightarrow WH$ analyses because of the requirements on the angular separation $\Delta\phi(\ell, \vec{p}_T^{\text{miss}})$ between the \vec{p}_T^{miss} and the lepton direction. The $Z' \rightarrow \ell\ell$ analysis includes events with a dilepton invariant mass $m_{\ell\ell} > 120$ GeV, which is incompatible with the $70 < m_{\ell\ell} < 110$ GeV selection used in the diboson channels, in which the Z boson is on-shell. The two searches for resonant HH bosons that decay to b quarks have common events explicitly removed [10].

In the $WV \rightarrow \ell\nu q\bar{q}$ channel [3] the background is estimated using a 2D fitting technique that scans the full jet mass range, and is therefore not independent of the $WH \rightarrow \ell\nu b\bar{b}$ channel. For this reason, in the W' , Z' , and V' interpretations, where the two signals might be present simultaneously, the “ α function” is used to estimate the background instead. This method considers only events in the m_j regions of the W and Z bosons, thereby preventing double counting of events in the Higgs boson mass region. The results of the alternative background estimation method are consistent with those obtained in the 2D fit, but the method is about 10% less sensitive. The main selections that define the exclusivity of the analyses are summarized in Table 1.

6. Systematic uncertainties

The systematic uncertainties originating from the background estimation in the individual channels are considered uncorrelated, because the backgrounds are determined from statistically independent control regions. The uncertainties arising from the reconstruction and calibration are instead correlated among the different

Table 1
Summary of the main selections that guarantee the exclusivity between individual final states. The symbol ℓ represents an electron or a muon; τ leptons are considered separately. If an entry is not preceded by “ \geq ”, the exact value is required. The AK4 b jets are additional b tagged AK4 jets that do not geometrically overlap with AK8 jets. The symbol “–” implies that no selection is applied.

Ref.	Channel	Final state	ℓ	τ_h	AK8 jets	AK8 jet mass	AK4 b jets
[1]	WW, WZ, ZZ	$q\bar{q}q\bar{q}$	0	0	≥ 2	$2[m_W, m_Z]$	–
[2]	WZ, ZZ	$\nu\nu q\bar{q}$	0	0	≥ 1	m_V	0
[3]	WW, WZ	$\ell\nu q\bar{q}$	1	–	≥ 1	see Sec. 5	0
[4]	WZ, ZZ	$\ell\ell q\bar{q}$	≥ 2	–	≥ 1	m_V	–
[5]	ZZ	$\ell\ell\nu\nu$	≥ 2	–	–	–	–
[6]	WH, ZH	$q\bar{q}b\bar{b}$	0	0	≥ 2	$[m_W, m_Z], m_H$	–
[7]	ZH	$\nu\nu b\bar{b}$	0	0	≥ 1	m_H	0
[7]	WH	$\ell\nu b\bar{b}$	1	0	≥ 1	m_H	0
[7]	ZH	$\ell\ell b\bar{b}$	≥ 2	0	≥ 1	m_H	–
[8]	WH, ZH	$q\bar{q}\tau\tau$	–	≥ 2	≥ 1	$[m_W, m_Z]$	0
[8]	HH	$\tau\tau b\bar{b}$	–	≥ 2	≥ 1	m_H	0
[9]	HH	$b\bar{b}b\bar{b}$	–	–	≥ 2	$2m_H$	–
[10]	HH	$b\bar{b}b\bar{b}$	–	–	1	m_H	≥ 2
[19]		$\ell\nu$	1	–	–	–	–
[20]		$\ell\ell$	≥ 2	–	–	–	–

Table 2
Summary of the main systematic uncertainties. The second column reports whether a systematic uncertainty is considered fully correlated or not across different channels. The third column indicates whether the uncertainty affects the yield, the shape of the distributions, or both, or if it induces migration (migr.) effects across search regions. The fourth column reports the smallest and largest effect of the uncertainty, among the yield, the migration, and the signal shape parameters. The symbols “s”, “b” indicate that the uncertainty affects the signal, the main backgrounds of the analysis, respectively. The treatment of non-dominant backgrounds is often different and not reported here. The symbol “f” indicates that the parameters are not constrained, or associated with large uncertainties as in the case of multi-dimensional fits. The entries labeled with “t” are treated differently depending on the interpretation of the exclusion limit, as discussed in Section 7. Uncertainties marked with “–” are not applicable or are negligible.

	Correlation	Type	Variation	$q\bar{q}q\bar{q}$ [1]	$\nu\nu q\bar{q}$ [2]	$\ell\nu q\bar{q}$ (2D fit) [3]	$\ell\ell q\bar{q}$ [4]	$\nu\nu\ell\ell$ [5]	$q\bar{q}b\bar{b}$ [6]	$(\nu\nu, \ell\nu, \ell\ell)b\bar{b}$ [7]	$(q\bar{q}, b\bar{b})\tau\tau$ [8]	$b\bar{b}b\bar{b}$ [9,10]	$\ell\nu$ [19]	$\ell\ell$ [20]
Bkg. modeling	no	shape	–	f	b	f	b	b	f	b	b	b	b	b
Bkg. normalization	no	yield	2–30%	f	b	f	b	b	f	b	b	b	b	b
Jet energy scale	yes	yield, shape	1–2%	s	s	s, b	s	–	s	s	s	s	–	–
Jet energy resolution	yes	yield, shape	3–7%	s	s	s, b	s	–	s	s	s	s	–	–
Jet mass scale	yes	yield, migr.	1–36%	s	s	s, b	s	–	s	s	s	s	–	–
Jet mass resolution	yes	yield, migr.	5–25%	s	s	s, b	s	–	s	s	s	s	–	–
Jet triggers	yes	yield	1–15%	s	–	–	–	–	s	–	–	s	–	–
e, μ id., iso., trigger	yes	yield, shape	1–3%	–	–	s	s	s, b	–	s	s	–	s, b	s, b
e, μ scale and res.	yes	yield, shape	1–6%	–	–	s	s	s, b	–	s	–	–	s, b	s, b
τ_h reco., id., iso.	yes	yield	6–13%	–	s	–	–	–	–	s	s	–	–	–
τ_h energy scale	yes	yield, shape	1–5%	–	–	–	–	–	–	–	s	–	–	–
τ_h high- p_T extr.	yes	yield, shape	18–30%	–	–	–	–	–	–	–	s	–	–	–
p_T^{miss} scale and res.	yes	yield	1–2%	–	s	s	–	s, b	–	s	s	–	s, b	–
p_T^{miss} triggers	yes	yield	1–2%	–	s	–	–	–	–	s	s	–	–	–
b quark identification	yes	yield, migr.	1–9%	–	s	s, b	–	–	s	s	s	s	–	–
τ_{21} identification	yes	yield, migr.	11–33%	s	s	s, b	s	–	s	–	s	s	–	–
V tagging high- p_T extr.	yes	yield, migr.	2–40%	s	s	s, b	s	–	s	–	s	s	–	–
m_H selection	yes	yield	6%	–	–	–	–	–	s	s	s	s	–	–
pp cross section	yes	yield	1–2%	s	s	–	s	–	s	s	s	s	s, b	–
Luminosity	yes	yield	2.5%	s	s	s	s	s, b	s	s	s	s	s, b	s, b
PDF and QCD accept.	yes	yield	1–2%	s	–	s	s	s, b	s	s	s	s	–	s, b
PDF and QCD norm.	yes	yield	2–78%	t	t	t	t	t, b	t	t	t	t	t, b	t, b

channels. These include the uncertainties in jet energy and resolution, and in the e, μ , and τ_h lepton energy, reconstruction, and identification. The uncertainties in the identification of the SM bosons that decay to quarks are dominant in final states containing at least one such decay, and originate from the m_j scale and resolution, the τ_{21} selection, and the b tagging. The uncertainties in the V tagging extrapolation to large jet p_T and the selection of events in the jet mass window of the Higgs boson are estimated by comparing the results with those obtained using the alternative HERWIG++ [73] shower model. These uncertainties affect the signal distribution, selection efficiency, and induce event migration effects between search regions. The uncertainties in the

proton-proton inelastic cross section [74], the integrated luminosity during the 2016 data-taking [75] and the kinematic acceptance of final-state particles, which affect the signal normalization, are also considered as correlated among channels. Theoretical uncertainties in the cross section and in the signal geometric acceptance related to the choice of PDFs used in the event generators [76], and the uncertainties in the factorization and renormalization scales, are evaluated according to the PDF4LHC recommendations [76]. The impact of these uncertainties on the signal cross section can be as large as 78%, depending on the signal mass and the initial state ($q\bar{q}$ or gg). A summary of the main systematic uncertainties is given in Table 2.

7. Statistical combination

No significant excess is observed above the SM background expectations. Upper limits are set at 95% confidence level (CL) [77,78] on the cross section of a heavy resonance, which is rescaled by a signal strength modifier parameter μ with uniform prior. Systematic uncertainties are represented by nuisance parameters θ , and affect both signal and background expectations [79]. Systematic uncertainties are considered fully (anti-)correlated when related to a common nuisance parameter, or uncorrelated when different nuisance parameters are used. The prior on these parameters is either flat (represented by the symbol “f” in Table 2) or log-normal distributed (identified with “s”, “b”, “t” in Table 2). The statistical procedure is based on a likelihood constructed as:

$$\mathcal{L}(\text{data}|\mu, \theta) = \prod_c \prod_i \mathcal{P}(\text{data}|\mu s_{c,i}(\theta) + b_{c,i}(\theta)) \prod_j p_j(\tilde{\theta}_j|\theta_j), \quad (1)$$

where \mathcal{P} represents the Poisson probability, and $p_j(\tilde{\theta}_j|\theta_j)$ is the frequentist pdf of the nuisance parameter θ_j and its default value $\tilde{\theta}_j$ associated with the j th uncertainty. The values $s_{c,i}(\theta)$ and $b_{c,i}(\theta)$ represent the number of signal and background events in the channel c and bin i , respectively. The test statistic is based on the profile likelihood ratio \tilde{q} :

$$\tilde{q}(\mu) = -2 \log \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu}, \hat{\theta}_{\hat{\mu}})}, \quad (2)$$

and the quantities $\hat{\mu}$, $\hat{\theta}_\mu$, $\hat{\theta}_{\hat{\mu}}$ are fixed to their best-fit value, and the range of μ is limited in the $0 \leq \hat{\mu} \leq \mu$ interval. The uncertainties that affect the signal normalization (PDFs and factorization and renormalization scales, marked with “t” in Table 2) are treated differently depending on how the exclusion is presented. When deriving upper limits on the cross section, these uncertainties are not varied in the fit, but are reported separately as the uncertainty of the theoretical cross sections from the model. When placing limits on the model parameters, these nuisance parameters are fixed at the best-fit values, in the same manner as to the other systematic uncertainties.

The upper limit on μ is derived from the 95% CL_s criterion, defined as $\text{CL}_s(\mu) = p(\mu)/(1 - p(0))$, such that $\text{CL}_s(\mu) = 0.05$. The quantities $p(\mu)$ and $1 - p(0)$ represent the probabilities to have a value of \tilde{q} equal to, or larger than the observed value in the signal or background ($\mu = 0$) hypotheses, respectively, and are derived from analytical functions using the asymptotic approximation [80]. This approximation leads to limits that are up to 30% stronger in regions with a small number of data events, compared to those obtained from the Monte Carlo generation of pseudo-experiments [79].

8. Results and interpretation

The data are in agreement with the expected background from SM processes. The largest deviation from the expected limit is observed in the V' model A at a mass of 1.3 TeV, with a local significance of 2.7 standard deviations, corresponding to a global significance of 1.6 standard deviations. The local significances are obtained in the asymptotic approximation [80], and the global significances are evaluated using the trial factors method [81].

The exclusion limit on the cross section of each diboson channel (WW, WZ, ZZ, WH, ZH, HH) is depicted in Fig. 1 for the combination of all contributing channels, reported in Table 1, according to the spin of the new resonance. The generated signal can be either

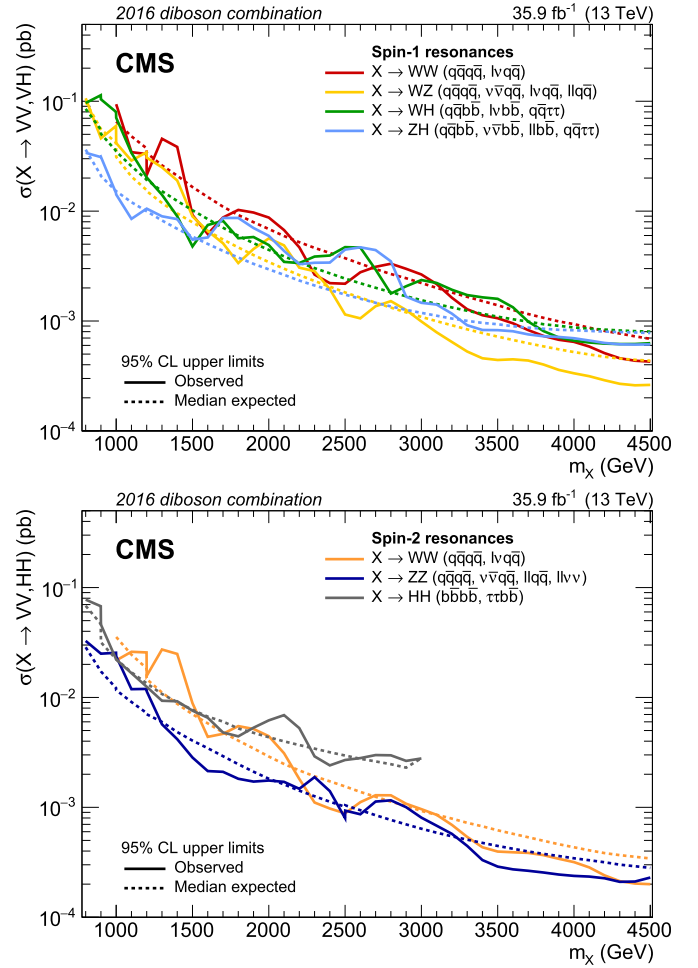


Fig. 1. Observed and expected 95% CL upper limits on the product of the cross section and branching fraction of a spin-1 (upper) or spin-2 resonance (lower) decaying to a pair of SM bosons.

a spin-1 heavy vector (W' or Z' , as in the HVT model) or a spin-2 boson (as in the bulk graviton model). In fact, the spin and polarization of the heavy resonance does affect the final state, signal acceptance, and selection efficiencies. The exclusion limits are not presented above 4.5 TeV, since at larger masses the background estimation procedure used in diboson analyses becomes less reliable because of the lack of events in data.

The combined exclusion limits for the spin-1 singlet hypotheses (W' or Z') in the HVT model B framework, where the branching fractions to SM bosons are dominant, are shown in Fig. 2. In this scenario, the contribution of the dilepton channels is negligible because their branching fraction is of the order of a few permil. In the VV analyses, the $V' \rightarrow VH$ signal is added to the $V' \rightarrow VV$ signal because the fraction of H jets passing the m_W and m_Z selections is not negligible and can contribute up to 30% to the total signal yield. The predictions of the HVT model B are superimposed on the exclusion limits, showing that a W' boson of mass below 4.3 TeV, and a Z' boson with mass below 3.7 TeV are excluded at 95% CL.

The HVT hypothesis is tested in Fig. 3 by combining all diboson channels, showing that a mass-degenerate state with mass below 4.5 TeV can be excluded in HVT model B, and extending the exclusion with respect to the best individual channel by approximately 700 GeV [1]. This result significantly improves the previous $\sqrt{s} = 8$ and 13 TeV CMS combination [82], which excluded a triplet of

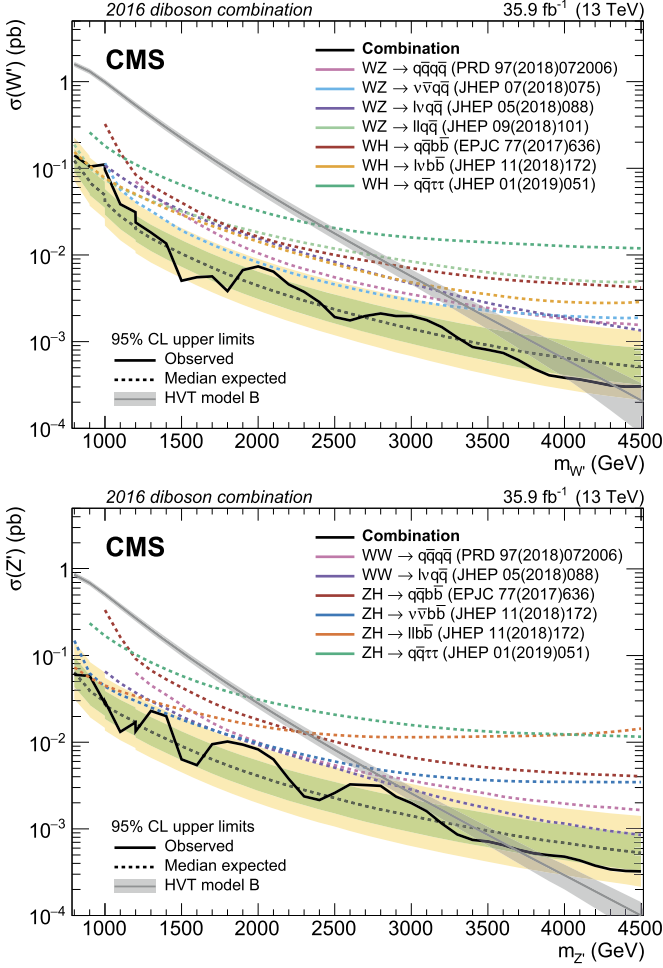


Fig. 2. Observed and expected 95% CL upper limits on the W' (upper) and Z' cross section (lower) as a function of the W' and Z' resonance mass. The inner green and outer yellow bands represent the ± 1 and ± 2 standard deviation variations on the expected limits of the statistical combination of the VV and VH channels considered. The expected limits in individual channels are represented by the colored dashed lines. The solid curves surrounded by the shaded areas show the cross sections predicted by the HVT model B and their uncertainties.

heavy resonances with masses up to 2.4 TeV in the same model. The dilepton resonances provide the most stringent results within the HVT model A framework, and are combined with the diboson searches in Fig. 3. A heavy triplet of V' resonances is excluded up to a mass of 5.0 TeV.

The exclusion limits on the resonance cross sections shown in Fig. 3 are also interpreted as limits in the $[g_H, g_V]$ plane of the HVT parameters. The excluded region of parameter space for narrow resonances obtained from the combination of all the channels is shown in Fig. 4. The dilepton and diboson searches constrain different regions of the parameter space, as the dilepton searches can probe the region where the coupling to the SM bosons approaches zero. In the triplet interpretation, the ratio of the W' to Z' cross sections is assumed to be determined by the ratio of the partonic luminosities, and to depend only weakly on the model parameters. The fraction of the parameter space where the natural width of the resonances is larger than the average experimental resolution of 5%, and the narrow-width approximation is thus invalid, is also indicated in Fig. 4.

In the spin-2 bulk graviton model, the WW , ZZ , and HH channels are combined, setting upper limits of up to 1.1 fb on the cross section of a graviton with mass up to 4.5 TeV. In the $\tilde{\kappa} = 0.5$ sce-

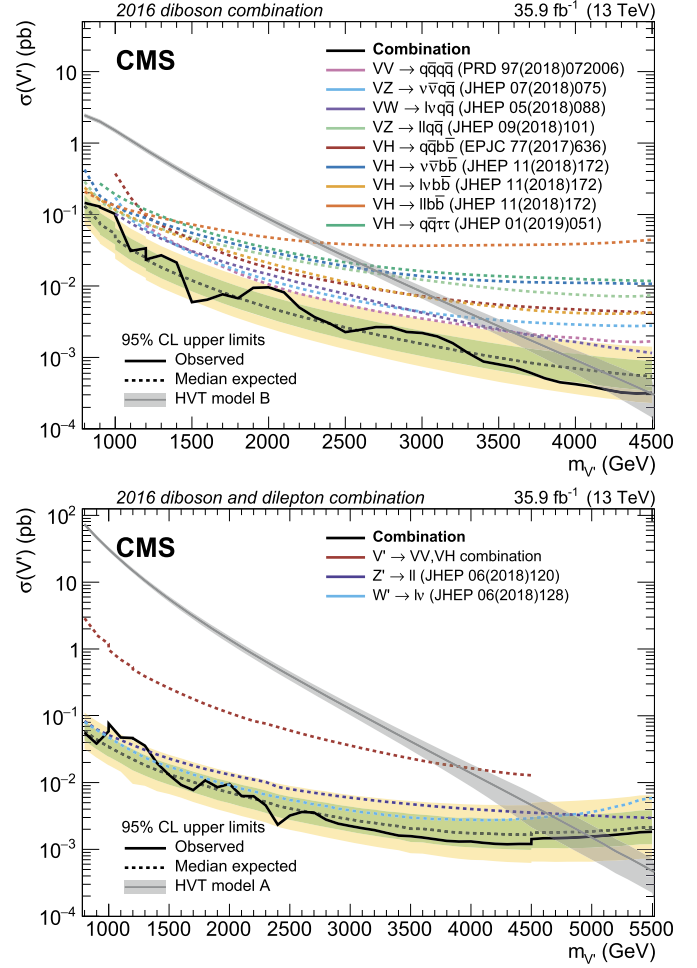


Fig. 3. Observed and expected 95% CL upper limits on cross sections as a function of the HVT triplet mass for the combination of all channels in the HVT model B (upper) and model A (lower). The inner green and outer yellow bands represent the ± 1 and ± 2 standard deviation variations on the expected limit. The solid curves surrounded by the shaded areas show the cross sections predicted by HVT models A and B and their uncertainties.

nario, a graviton with a mass smaller than 850 GeV is excluded at 95% CL, as shown in Fig. 5. Larger $\tilde{\kappa}$ values increase the production cross sections, but also the graviton natural width, which can be comparable or larger than the experimental resolution. In these cases, the narrow-width approximation is no longer valid.

These results represent the most stringent limits on heavy vector models set by CMS and are comparable at large V' mass to the limits obtained the ATLAS in the combination of similar channels [45]. At lower masses, the ATLAS combination excludes smaller cross sections because of the inclusion of final states with three or more leptons. The exclusion limits in the bulk graviton model are not directly comparable because of the large $\tilde{\kappa} = 1.0$ parameter adopted by ATLAS, which increases the cross section but also implies a non-negligible natural width.

9. Summary

A statistical combination of searches for heavy resonances decaying into pairs of vector bosons, a vector boson and a Higgs boson, two Higgs bosons, or pairs of leptons, has been presented. The results are based on data collected by the CMS experiment at $\sqrt{s} = 13$ TeV during 2016 corresponding to an integrated luminosity of 35.9 fb^{-1} . In models with warped extra dimensions, upper

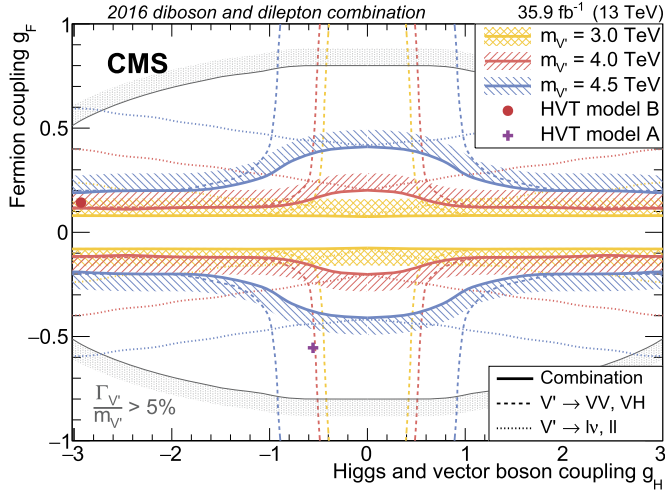


Fig. 4. Observed exclusion limits on the couplings of heavy vector resonances to fermions and SM vector bosons and the Higgs boson for the statistical combination (solid lines) of the dilepton (dotted lines) and diboson channels (dashed lines). Three resonance masses hypotheses (3.0, 4.0, and 4.5 TeV) are considered. The hatched bands indicate the regions excluded. The areas bounded by the thin gray contour lines correspond to regions where the resonance widths (Γ_V) are predicted to be larger than the average experimental resolution (5%).

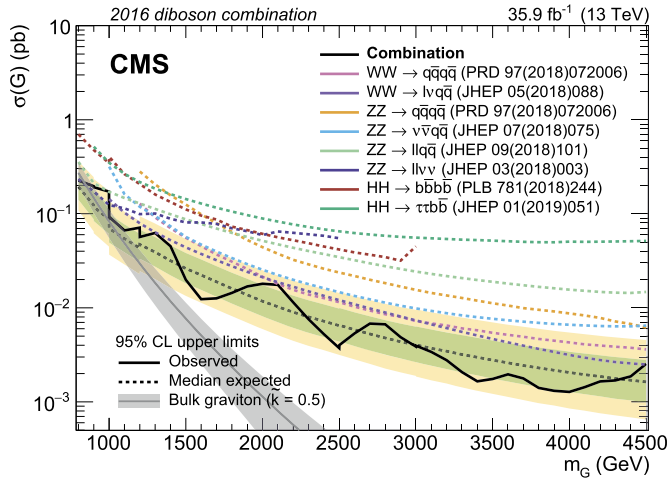


Fig. 5. Observed and expected 95% CL upper limit on the cross section of the spin-2 bulk graviton as a function of its mass for the statistical combination of the WW, ZZ, and HH channels. The inner green and outer yellow bands represent the ± 1 and ± 2 standard deviation variations on the expected limit. The solid curve and its shaded area represent the cross section derived with the parameter $\tilde{\kappa} = 0.5$ and the associated uncertainty.

limits of up to 1.1 fb are set at 95% confidence level on the production cross section of the spin-2 bulk graviton. For models with a triplet of narrow spin-1 resonances, heavy vector bosons with masses below 5.0 and 4.5 TeV are excluded at 95% confidence level in models where the W' and Z' bosons couple predominantly to fermions and bosons, respectively. In the latter, the statistical combination extends the exclusion limit by 700 GeV as compared to the best individual channel.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort.

In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NK-FIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NK-FIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, grant no. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); The Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, J. Luetic, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov², C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrkowski, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, J. Martins⁵, D. Matos Figueiredo, M. Medina Jaime⁶, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, D.S. Lemos, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁷, X. Gao⁷, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G.M. Chen, H.S. Chen, M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen⁸, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁸, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Z. Hu, Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, S. Ceci, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁹, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger¹⁰, M. Finger Jr.¹⁰, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran^{11,12}, S. Elgammal¹²

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹³, M. Titov

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

C. Amendola, F. Beaudette, P. Busson, C. Charlot, B. Diab, R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili¹⁵

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze¹⁰

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, M. Erdmann, S. Erdweg, T. Esch, B. Fischer, R. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, M. Rieger, A. Schmidt, S.C. Schuler, A. Sharma, S. Thüer, S. Wiedenbeck

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

G. Flügge, W. Haj Ahmad¹⁶, O. Hlushchenko, T. Kress, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁷

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, C. Asawatangtrakuldee, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁸, V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁹, A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, N.Z. Jomhari, H. Jung, A. Kasem¹⁸, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, J. Lidrych, K. Lipka, W. Lohmann²⁰, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebick

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, A. Ebrahimi, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner,

R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, D. Marconi, J. Multhaupt, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, P. Goldenzweig, M.A. Harrendorf, F. Hartmann¹⁷, U. Husemann, S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Weber, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, A. Stakia, K. Theofilatos, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók²¹, M. Csanad, P. Major, K. Mandal, A. Mehta, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²², F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T.F. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²³, C. Kar, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak²⁴, S. Roy Chowdhury, D.K. Sahoo²³, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj²⁵, M. Bharti²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, M. Maity²⁶, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁶, M. Sharan, B. Singh²⁵, S. Thakur²⁵

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, R. Venditti^a, P. Verwilligen^a

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,28}, S. Marcellini^a, G. Masetti^a, F.L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b,29}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,29}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli ^a, R. Ceccarelli, K. Chatterjee ^{a,b}, V. Ciulli ^{a,b}, C. Civinini ^a, R. D'Alessandro ^{a,b}, E. Focardi ^{a,b}, G. Latino, P. Lenzi ^{a,b}, M. Meschini ^a, S. Paoletti ^a, L. Russo ^{a,30}, G. Sguazzoni ^a, D. Strom ^a, L. Viliani ^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo ^{a,b}, F. Ferro ^a, R. Mulargia ^{a,b}, E. Robutti ^a, S. Tosi ^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia ^a, A. Beschi ^{a,b}, F. Brivio ^{a,b}, V. Ciriolo ^{a,b,17}, S. Di Guida ^{a,b,17}, M.E. Dinardo ^{a,b}, P. Dini ^a, S. Fiorendi ^{a,b}, S. Gennai ^a, A. Ghezzi ^{a,b}, P. Govoni ^{a,b}, L. Guzzi ^{a,b}, M. Malberti ^a, S. Malvezzi ^a, D. Menasce ^a, F. Monti ^{a,b}, L. Moroni ^a, G. Ortona ^{a,b}, M. Paganoni ^{a,b}, D. Pedrini ^a, S. Ragazzi ^{a,b}, T. Tabarelli de Fatis ^{a,b}, D. Zuolo ^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^a, N. Cavallo ^{a,c}, A. De Iorio ^{a,b}, A. Di Crescenzo ^{a,b}, F. Fabozzi ^{a,c}, F. Fienga ^a, G. Galati ^a, A.O.M. Iorio ^{a,b}, L. Lista ^{a,b}, S. Meola ^{a,d,17}, P. Paolucci ^{a,17}, B. Rossi ^a, C. Sciacca ^{a,b}, E. Voevodina ^{a,b}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi ^a, N. Bacchetta ^a, D. Bisello ^{a,b}, A. Boletti ^{a,b}, A. Bragagnolo, R. Carlin ^{a,b}, P. Checchia ^a, P. De Castro Manzano ^a, T. Dorigo ^a, U. Dosselli ^a, F. Gasparini ^{a,b}, U. Gasparini ^{a,b}, A. Gozzelino ^a, S.Y. Hoh, P. Lujan, M. Margoni ^{a,b}, A.T. Meneguzzo ^{a,b}, J. Pazzini ^{a,b}, M. Presilla ^b, P. Ronchese ^{a,b}, R. Rossin ^{a,b}, F. Simonetto ^{a,b}, A. Tiko, M. Tosi ^{a,b}, M. Zanetti ^{a,b}, P. Zotto ^{a,b}, G. Zumerle ^{a,b}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

A. Braghieri ^a, P. Montagna ^{a,b}, S.P. Ratti ^{a,b}, V. Re ^a, M. Ressegotti ^{a,b}, C. Riccardi ^{a,b}, P. Salvini ^a, I. Vai ^{a,b}, P. Vitulo ^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini ^{a,b}, G.M. Bilei ^a, C. Cecchi ^{a,b}, D. Ciangottini ^{a,b}, L. Fanò ^{a,b}, P. Lariccia ^{a,b}, R. Leonardi ^{a,b}, E. Manoni ^a, G. Mantovani ^{a,b}, V. Mariani ^{a,b}, M. Menichelli ^a, A. Rossi ^{a,b}, A. Santocchia ^{a,b}, D. Spiga ^a

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

K. Androsov ^a, P. Azzurri ^a, G. Bagliesi ^a, V. Bertacchi ^{a,c}, L. Bianchini ^a, T. Boccali ^a, R. Castaldi ^a, M.A. Ciocci ^{a,b}, R. Dell'Orso ^a, G. Fedì ^a, F. Fiori ^{a,c}, L. Giannini ^{a,c}, A. Giassi ^a, M.T. Grippo ^a, F. Ligabue ^{a,c}, E. Manca ^{a,c}, G. Mandorli ^{a,c}, A. Messineo ^{a,b}, F. Palla ^a, A. Rizzi ^{a,b}, G. Rolandi ³¹, A. Scribano ^a, P. Spagnolo ^a, R. Tenchini ^a, G. Tonelli ^{a,b}, A. Venturi ^a, P.G. Verdini ^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

F. Cavallari ^a, M. Cipriani ^{a,b}, D. Del Re ^{a,b}, E. Di Marco ^{a,b}, M. Diemoz ^a, E. Longo ^{a,b}, B. Marzocchi ^{a,b}, P. Meridiani ^a, G. Organtini ^{a,b}, F. Pandolfi ^a, R. Paramatti ^{a,b}, C. Quaranta ^{a,b}, S. Rahatlou ^{a,b}, C. Rovelli ^a, F. Santanastasio ^{a,b}, L. Soffi ^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, R. Salvatico^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi^{a,b}, A. Staiano^a

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, A. Da Rold^{a,b}, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

B. Kim, D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, I. Yoon, G.B. Yu

Seoul National University, Seoul, Republic of Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, I. Watson

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns³²

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

Z.A. Ibrahim, F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁴, R. Lopez-Fernandez, R.I. Rabadan-Trejo, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{36,37}, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁸, E. Kuznetsova³⁹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tilsov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko⁴⁰, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov⁴¹, M. Danilov⁴¹, D. Philippov, E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁷, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Barnyakov⁴³, V. Blinov⁴³, T. Dimova⁴³, L. Kardapoltsev⁴³, Y. Skovpen⁴³

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic⁴⁵, J. Milosevic, M. Stojanovic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

K. Malagalage

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, E. Bossini, C. Botta, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita⁴⁶, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, A. Jafari, P. Janot, O. Karacheban²⁰, J. Kaspar, J. Kieseler, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁷, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, M. Quinto, D. Rabaday, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁴⁷, J. Steggemann, V.R. Tavolaro, D. Treille, A. Tsiros, A. Vartak, M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁴⁸, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, T. Reitspiess, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁹, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

Universität Zürich, Zurich, Switzerland

T.H. Doan, C.M. Kuo, W. Lin, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Bat, F. Boran, S. Cerci⁵⁰, S. Damarseckin⁵¹, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Emine Gulpinar Guler⁵², Y. Guler, I. Hos⁵³, C. Isik, E.E. Kangal⁵⁴, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁵, S. Ozturk⁵⁶, A.E. Simsek, D. Sunar Cerci⁵⁰, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak⁵⁷, G. Karapinar⁵⁸, M. Yalvac

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, B. Kaynak, Ö. Özçelik, S. Ozkorucuklu⁶¹, S. Tekten, E.A. Yetkin⁶²

Bogazici University, Istanbul, Turkey

A. Cakir, Y. Komurcu, S. Sen⁶³

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

F. Ball, E. Bhal, S. Bologna, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, S. Paramesvaran, B. Penning, T. Sakuma, S. Seif El Nasr-Storey, D. Smith, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶⁴, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, Gurpreet Singh Chahal⁶⁵, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash⁶⁶, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁷, N. Wardle, D. Winterbottom, J. Wright, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

K. Call, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez, R. Uniyal

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burklee, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁷, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁸, R. Syarif, E. Usai, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang, J. Yoo

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, Allison Reinsvold Hall, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena, G. Rakness, F. Ravera, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding,

L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, V. Cherepanov, D. Curry, F. Errico, R.D. Field, S.V. Gleyzer, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, T. Perry, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, C. Mills, T. Roy, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu

University of Illinois at Chicago (UIC), Chicago, USA

M. Alhusseini, B. Bilki⁵², W. Clarida, K. Dilsiz⁶⁹, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷⁰, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, M. Swartz, M. Xiao

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, T. Isidori, S. Khalil, J. King, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Baty, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, S. Guts, P. Hansen, J. Hiltbrand, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, J. Bueghly, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, USA

S. Cooperstein, G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully, Z. Wang

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

Rutgers, The State University of New Jersey, Piscataway, USA

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷³, S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, G. Cummings, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

Wayne State University, Detroit, USA

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber⁷⁴, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

¹ Also at Vienna University of Technology, Vienna, Austria.

² Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

³ Also at Universidade Estadual de Campinas, Campinas, Brazil.

⁴ Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

⁵ Also at UFMS/CPNA – Federal University of Mato Grosso do Sul/Campus of Nova Andradina, Nova Andradina, Brazil.

⁶ Also at Universidade Federal de Pelotas, Pelotas, Brazil.

⁷ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁸ Also at University of Chinese Academy of Sciences, Beijing, China.

⁹ Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia.

¹⁰ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹¹ Also at Suez University, Suez, Egypt.

¹² Now at British University in Egypt, Cairo, Egypt.

¹³ Also at Purdue University, West Lafayette, USA.

¹⁴ Also at Université de Haute Alsace, Mulhouse, France.

¹⁵ Also at Tbilisi State University, Tbilisi, Georgia.

¹⁶ Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

¹⁷ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

¹⁸ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

¹⁹ Also at University of Hamburg, Hamburg, Germany.

²⁰ Also at Brandenburg University of Technology, Cottbus, Germany.

²¹ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

²² Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

²³ Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

²⁴ Also at Institute of Physics, Bhubaneswar, India.

²⁵ Also at Shoolini University, Solan, India.

- ²⁶ Also at University of Visva-Bharati, Santiniketan, India.
- ²⁷ Also at Isfahan University of Technology, Isfahan, Iran.
- ²⁸ Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ²⁹ Also at Centro Siciliano di Fisica Nucleare e di Struttura della Materia, Catania, Italy.
- ³⁰ Also at Università degli Studi di Siena, Siena, Italy.
- ³¹ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ³² Also at Riga Technical University, Riga, Latvia.
- ³³ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ³⁴ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ³⁵ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ³⁶ Also at Institute for Nuclear Research, Moscow, Russia.
- ³⁷ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ³⁸ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ³⁹ Also at University of Florida, Gainesville, USA.
- ⁴⁰ Also at Imperial College, London, United Kingdom.
- ⁴¹ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁴² Also at California Institute of Technology, Pasadena, USA.
- ⁴³ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁴⁴ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁴⁵ Also at University of Belgrade, Belgrade, Serbia.
- ⁴⁶ Also at INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy.
- ⁴⁷ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁴⁸ Also at Universität Zürich, Zurich, Switzerland.
- ⁴⁹ Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ⁵⁰ Also at Adiyaman University, Adiyaman, Turkey.
- ⁵¹ Also at Sirnak University, Sirnak, Turkey.
- ⁵² Also at Beykent University, Istanbul, Turkey.
- ⁵³ Also at Istanbul Aydin University, Istanbul, Turkey.
- ⁵⁴ Also at Mersin University, Mersin, Turkey.
- ⁵⁵ Also at Piri Reis University, Istanbul, Turkey.
- ⁵⁶ Also at Gaziosmanpasa University, Tokat, Turkey.
- ⁵⁷ Also at Ozyegin University, Istanbul, Turkey.
- ⁵⁸ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁵⁹ Also at Marmara University, Istanbul, Turkey.
- ⁶⁰ Also at Kafkas University, Kars, Turkey.
- ⁶¹ Also at Istanbul University, Istanbul, Turkey.
- ⁶² Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁶³ Also at Hacettepe University, Ankara, Turkey.
- ⁶⁴ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁶⁵ Also at Institute for Particle Physics Phenomenology Durham University, Durham, United Kingdom.
- ⁶⁶ Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁶⁷ Also at Bethel University, St. Paul, USA.
- ⁶⁸ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁶⁹ Also at Bingol University, Bingol, Turkey.
- ⁷⁰ Also at Sinop University, Sinop, Turkey.
- ⁷¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ⁷² Also at Texas A&M University at Qatar, Doha, Qatar.
- ⁷³ Also at Kyungpook National University, Daegu, Republic of Korea.
- ⁷⁴ Also at University of Hyderabad, Hyderabad, India.